PRODUCTION OF CHARMED MESONS IN
NEUTRINO INTERACTIONS IN HYDROGEN

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ABSTRACT

Production of charmed mesons has been observed in neutrino-hydrogen interactions in 285 000 photographs of BEBC exposed to the CERN wideband neutrino beam. In ~ 6000 charged current events, two events have been found each giving a three-constraint kinematical fit with production of only one strange particle, namely a K^- , which is identified by its characteristic reaction $K^- p \rightarrow \Sigma^- \pi^+$. These events are thus examples of $\Delta S = -\Delta Q$ reactions corresponding to charm production on a valence quark. For both events the effective mass of a (K^- + pions) system is equal to the $D^0(1863)$ mass while the effective mass of this system plus a π^+ is equal to the $D^{*+}(2009)$ mass. The mass difference $\Delta M = M(D^{*+}) - M(D^0)$ is 145.2 ± 0.6 MeV. The first event is interpreted as $\nu p \rightarrow \mu^- p D^{*+}$ and the second as $\nu p \rightarrow \mu^- p D^{*+} \pi^+ \pi^-$, both with $D^{*+} \rightarrow D^0 \pi^+$. The inclusive cross section for D^{*+} production has been determined for all events by assuming that each negative track in turn is a K^- and using the fact that the error on ΔM is small. It is found that the cross section $\sigma(\nu p \rightarrow \mu^- D^{*+} + \text{anything})$ relative to $\sigma(\nu p \rightarrow \mu^- + \text{anything})$, above the D^* threshold is $(4.1 \pm 2.4)\%$.

Production of charmed particles should occur relatively frequently in neutrino interactions, but direct evidence for charmed mesons and baryons has been hard to obtain, though di-lepton events are strong indirect evidence [1]. So far, only two events are known where the evidence could be firmly based on completely identified final states [2]. Both these events are at low energy and are interpreted as cases of production of charmed baryons, Λ_c . For charmed mesons, an enhancement in the $(K^0\pi^+\pi^-)$ mass distribution near 1870 MeV has given evidence [3] for the production of D^0 mesons decaying into $(K^0\pi^+\pi^-)$ in $(0.7 \pm 0.2)\%$ of all charged current (CC) events. However, no direct unambiguous example has been reported for charmed meson production.

In this paper two events are described that are interpreted unambiguously as first examples of production of the charmed meson D^{*+} (2009) decaying into D^0 (1863) plus a pion. Both events appear to violate the $\Delta S = +\Delta Q$ rule, thus indicating that charm production occurred on a valence quark. The inclusive production of D^{*+} has been studied and its rate relative to the total charged current cross section is determined.

The data were obtained from an exposure of the 3.7 m BEBC bubble chamber filled with hydrogen to the CERN wideband neutrino beam produced by 350 GeV protons from the SPS accelerator. The magnetic field of BEBC is 3.5 T. The results reported here are based on a sample of ~ 6500 CC events with an average energy of 45 GeV, representing about 3/4 of the final sample expected in the 285 000 photographs taken. Preliminary results from the experiment have been reported [4]. To be accepted, the CC events were required to have visible energy, E_{vis} , greater than 5 GeV and a negative muon with momentum $p^\mu > 3$ GeV/c. The muons were identified by a two-plane External Muon Identifier (EMI) whose efficiency is 98% for $p^\mu > 10$ GeV/c. The antineutrino contamination in the beam was negligible ($\sim 1\%$).

The first event, shown in fig. 1, has five outgoing tracks whose momenta are given in table 1. One of the negative tracks with momentum 42.4 GeV/c leaves the chamber and gives two correlated hits in the two

EMI planes, crossing a thickness of material equivalent to 223 cm of steel corresponding to twelve absorption lengths and is therefore taken to be the μ^- . The second negative track is a K^- by its identifiable secondary interaction $K^- + p \rightarrow \Sigma^- + \pi^+$, where both the Σ^- and the π^+ show their characteristic decays (in addition, the neutron from the decay of the Σ^- hits a proton to give a short visible proton recoil). Of the positive tracks, the slowest one, called P_3 in table 1, can be directly identified as a pion by its $\pi \rightarrow \mu$ decay in flight. The other two positive tracks, P_1 and P_2 , leave the chamber. Using energy and momentum conservation, an acceptable three-constraint, 3C, fit is obtained only when P_2 is taken as a proton and P_1 as a π^+ . All the 27 complete measurements of the event performed at two laboratories give the same unique 3C fit with an average fit probability of 30% (no other hypothesis was found to fit the event with a probability greater than 10^{-4}). The reaction is then

$$\nu p \rightarrow \mu^- p K^- \pi^+ \pi^+. \quad (1)$$

The second event, shown in fig. 2, has nine prongs whose momenta are given in table 1. The fastest negative particle, N_1 , of 13.8 GeV/c gives two correlated hits in the EMI planes crossing a thickness of 257 cm of steel-equivalent corresponding to 14 absorption lengths, and is taken as a μ^- . Another negative track, N_3 , of 1.4 GeV/c, gives a complicated chain of secondary interactions, the first of which gives a single four-constraint fit to backwards $K^- p$ elastic scattering. The backward-emitted negative track is identified as a K^- which comes to rest and gives the characteristic reaction $K^- p \rightarrow \Sigma^- \pi^+$, where the Σ^- interacts to produce a Λ whose decay is observed. Thus, track N_3 is a K^- . The other two negative tracks, N_2 and N_4 , leave the chamber. Of the five positive tracks, three of them, P_3 , P_4 and P_5 , make elastic scatters and are identified as π^+ 's. The fastest positive track, P_1 , of 0.99 GeV/c is unambiguously identified as a proton by its rate of energy loss along the track and by its ionization (bubble density). The fifth positive track, P_2 , is not a proton by ionization.

The measurements made at two laboratories all yield a unique 3C fit to the reaction

$$\nu p \rightarrow \mu^- p K^- \pi^+ \pi^+ \pi^+ \pi^+ \pi^- \pi^-, \quad (2)$$

when P_2 , N_2 and N_4 are taken as pions. The average of the fit probabilities obtained is $\sim 70\%$ and the next highest 3C fit probability for other mass assignments is less than $5 \cdot 10^{-3}$.

Both the reactions (1) and (2) produce a single strange particle, a K^- . The strangeness is thus -1. This is a violation of the $\Delta S = +\Delta Q$ rule, but is consistent with the $\Delta S = -\Delta Q$ expected for a reaction where the struck d-quark of charge $Q = -1/3$ and strangeness $S = 0$, is converted into a charmed quark with charge $+2/3$, which then decays into an s-quark with $S = -1$ (plus other non-strange quarks). It is important to check that the two events cannot be interpreted otherwise than by emission of a single strange particle. For both events:

- (a) It is impossible to take a pion as a kaon and keep a 3C fit of acceptable probability.
- (b) It is possible to add a π^0 in the forward beam direction and conserve energy and momentum, but this does not affect the $\Delta S = -\Delta Q$ assignment.
- (c) It is possible to add a K^0 in the forward beam direction which would change the $\Delta S = -\Delta Q$ interpretation. However, for each event such a K^0 would have unusual characteristics with small $p_{\perp}$ (< 30 MeV/c) and large p_L (> 25 GeV/c) relative to the neutrino beam direction. Of all the 289 K^0 particles observed in the CC events, none has a $p_{\perp} < 35$ MeV/c. Furthermore, those with small $p_{\perp}$ also have small p_L values (all K^0 events with $p_{\perp} < 100$ MeV/c have $p_L < 5$ GeV/c).
- (d) For event 1 it would be possible to interchange the π^+ and proton mass assignments of tracks P_1 and P_2 and compensate by adding a K_L^0 of ~ 1 GeV/c going in the forward beam direction. The probability of having a K^0 with $p_{\perp}$ of < 0.03 GeV/c to the neutrino beam direction in a few per cent.

(e) For event 1, the proton assignment of track P_2 could be replaced by the π^+ or K^+ assignment and, to compensate, a neutron could be emitted in the forward direction with three different possible momenta, of 1.77, 2.07 or 2.5 GeV/c. The probability of having a neutron with $p_{\perp}$ to the beam direction of < 0.03 GeV/c is expected again to be about few per cent.

For event 2, cases (d) and (e) are excluded because track P_1 is unambiguously identified as a proton. In conclusion, the probabilities that a second strange particle is emitted are less than a few per cent in event 1 and $< 10^{-4}$ in event 2.

We now consider effective masses of the particle sub-systems. In the first event the effective masses of the $(K^-\pi^+\pi^+)$ and $(K^-\pi^+)$ systems (where P_1 is the π^+ removed) are 2011 ± 6 and 1865 ± 4 MeV, respectively. These values are in good agreement with the D^{*+} and D^0 masses of 2008.6 ± 1.0 and 1863.3 ± 0.9 MeV, respectively [5]. In the second event, the effective masses of the $(K^-\pi^+\pi^+\pi^-)$ system (tracks N_3, P_2, P_3, P_4, N_2) and of the $(K^-\pi^+\pi^-)$ system (tracks N_3, P_2, P_3, N_2) are 2013 ± 4 and 1868 ± 4 MeV. This strongly suggests that in both events a charmed meson D^{*+} is produced which decays to $D^0\pi^+$. A more stringent test is the value of the mass difference ΔM , where

$$\Delta M = M(D^{*+}) - M(D^0), \quad (3)$$

which from the world average [5] is 145.3 ± 0.5 MeV. For the first event we obtain $\Delta M = 145.2 \pm 0.5$ MeV and for the second event 145.2 ± 0.6 MeV. The small error, which provides the stringent test, comes from the closeness of ΔM to the pion mass of 139 MeV. Thus, it is concluded that the first event corresponds to the reaction

and the second to the reaction

Further characteristics of these two events (E_{vis} , x , y , z , ...) are given in table 2.

In order to estimate the rate of D^{*+} production in CC events, we have studied the inclusive production of D^{*+} .

For each identified CC event, every negative track in turn was assumed to be a K^- and the other tracks to be pions unless otherwise identified. The effective mass of each system of (K^- + pions) which had an overall neutral charge, i.e. ($K^- \pi^+$), ($K^- \pi^+ \pi^-$), was then calculated and if it lay in the D^0 mass range, 1840 to 1890 MeV, then a further π^+ from the event was added and the new effective mass, i.e. of ($K^- \pi^+ \pi^+$), ($K^- \pi^+ \pi^+ \pi^-$), respectively, was calculated. The difference between these two masses, ΔM , thus obtained, is plotted in figs 3(a) and 3(b) for the cases of ($K^- \pi^+ \pi^+ \pi^-$) to ($K^- \pi^+ \pi^+ \pi^-$) and of ($K^- \pi^+ \pi^+$) to ($K^- \pi^+$), respectively^(*). A similar search for production of D^{*+} which decays into $D^0 \pi^+$ was made with events in which a K^0 was observed to decay, now requiring that the ($K^0 \pi^+ \pi^-$) effective mass be in the D^0 mass range (1840 to 1890 MeV). The ΔM for the possible decays ($K^0 \pi^+ \pi^- \pi^+$) to ($K^0 \pi^+ \pi^-$) is shown in fig. 3(c)^(**).

The sum of the three distributions in figs 3(a)-3(c) is plotted in fig. 3(d). A peak can be seen near the expected ΔM of 145 MeV. In order to determine the shape of the background, two neighbouring mass bins of the D^0 were taken, from 1700 to 1800 MeV and from 1900 to 2000 MeV, and as before, the ΔM values were obtained. The resultant shape of the background

(*) The two events described in the first part of this letter lie in the ΔM enhancements near 145 MeV, event 1 in fig. 3(a) and event 2 in fig. 3(b).

(**) The event in fig. 3(c) near $\Delta M = 145$ MeV is identified as $\nu p \rightarrow \mu^- D^{*+} K^+ + \dots$, and hence probably corresponding to charm production from the quark sea.

is plotted as a dotted curve in fig. 3(d), normalized to the number of events outside the mass band 143 to 147 MeV. The signal is thus found to be 7 ± 4 events.

Assuming that the branching ratios of D^0 into $(K^- \pi^+)$, $(K^- \pi^+ \pi^+ \pi^-)$ and $(K^0 \pi^+ \pi^-)$ are $(1.8 \pm 0.5)\%$, $(3.5 \pm 0.9)\%$ and $(4.4 \pm 1.1)\%$, respectively, and that of $D^{*+} \rightarrow D^0$ is $60 \pm 15\%$ [5], and taking into account the K^0 detection efficiency, then the fraction of CC events giving D^{*+} production (above the D^* threshold corresponding to the hadronic mass $W = 2.9$ GeV) is

$$\frac{\sigma(\nu p \rightarrow \mu^- D^{*+} + \text{anything})}{\sigma(\nu p \rightarrow \mu^- + \text{anything})} = (4.1 \pm 2.4)\%. \quad (6)$$

In calculating these ratios a correction has been made for the tail of events having a measured D^0 mass outside the acceptance band of 1840 to 1890 MeV. No correction was made for the geometrical efficiency of the EMI, as this error is small.

As it is possible that the D^* events could come from associated $D^{*-} D^{*+}$ production, the procedure was repeated looking for $\bar{D}^{*-}$ production (i.e. each non-identified positive track was in turn taken to be a K^+ , etc.), but no enhancement was observed in the ΔM mass distribution.

In conclusion, two unambiguous examples of $\Delta S = -\Delta Q$ events are observed with production of D^{*+} decaying into $D^0 \pi^+$ in three-constraint fit events. The fraction of CC events with D^{*+} production was estimated to be $(4.1 \pm 2.4)\%$, above the D^* threshold.

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TABLE 1

Description of tracks produced in events 1 and 2

Particle	Momentum MeV/c	Assignment	Identified by
<u>Event 1</u>			
P ₁	3590 ± 11	π_1^+	Kinematic fit
P ₂	1736 ± 5	p	Kinematic fit
P ₃	229 ± 1	π_2^+	Ionization, $\pi^+ \rightarrow \mu^+ \nu$ decay (unique fit)
N ₁	42 360 ± 290	μ^-	EMI
N ₂	318 ± 1	K^-	Ionization, energy loss, range, secondary interaction
<u>Event 2</u>			
P ₁	991 ± 3	p	Ionization, energy loss
P ₂	925 ± 2	π_1^+	Not a proton by ionization, kinematic fit
P ₃	437 ± 1	π_2^+	Ionization, elastic interaction
P ₄	357 ± 2	π_3^+	Ionization, elastic interaction
P ₅	299 ± 2	π_4^+	Ionization, elastic interaction
N ₁	13 772 ± 52	μ^-	EMI
N ₂	2408 ± 5	π_1^-	Kinematic fit
N ₃	1409 ± 4	K^-	Elastic scattering (unique fit), further interactions
N ₄	1102 ± 2	π_2^-	Kinematic fit

TABLE 2

Characteristics of events 1 and 2

	Event 1	Event 2
Final state	$\mu^- D^{*+} p$	$\mu^- D^{*+} \pi^+ \pi^- p$
$M(D^0)$, MeV	1865 ± 4	1868 ± 4
$M(D^{*+})$, MeV	2011 ± 6	2013 ± 4
ΔM , MeV	145.2 ± 0.5	145.2 ± 0.6
E_ν , GeV	47.8 ± 0.3	21.3 ± 0.05
Q^2 , GeV ²	1.21	0.53
$\nu = E_\nu - E_\mu$, GeV	5.49	7.56
$x = Q^2/2M\nu$	0.12	0.04
$y = \nu/E_\nu$	0.11	0.35
$z(D^{*}) = E(D^{*})/E_H$	0.69	0.67
$p_\perp(D^{*})^{(a)}$, GeV/c	0.52	0.33
$M(pD^{*})$, MeV	3156 ± 4	3172 ± 4

(a) Transverse momentum of D^{*} with respect to the axis of the hadron system.

FIGURE CAPTIONS

- Fig. 1 (a) Photograph of event 1 with charmed meson D^{*+} production as described in the text.
- (b) Drawing of event 1 with labelling of tracks and list of sequence of interactions and decays.
- Fig. 2 (a) Photograph of event 2 with charmed D^{*+} production as described in the text.
- (b) Drawing of event 2 with labelling of tracks and list of sequence of interactions and decays.
- Fig. 3 Distribution of the mass difference ΔM between the effective mass corresponding to a possible D^{*+} mass and the effective mass with one π^+ removed corresponding to a possible D^0 mass. Only one combination per bin per event is taken:
- (a) For $K^-\pi^+\pi^+\pi^-\pi^+$ decaying to $K^-\pi^+\pi^+\pi^-$,
- (b) For $K^-\pi^+\pi^+$ decaying to $K^-\pi^+$,
- (c) $K^0\pi^+\pi^-\pi^+$ decaying to $K^0\pi^+\pi^-$,
- (d) the sum of (a), (b) and (c).

Moments

fig. 3